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COLLAPSED OBJECTS WITHIN DIFFUSE STARS

Richard Stothers

Institute for Space Studies, Goddard Space Flight

Center, NASA, New York, New York 10025

and

Andrew Cheng

Department of Physics, Columbia University,

New York, New York 10027

ABSTRACT

If a collapsed object is placed at the center of a diffuse star, most of the diffuse matter will, in a typical case, be rapidly blown away as a result of secular instability induced by the luminosity of accreted material. Clouds of matter around compact objects like neutron stars and black holes must possess relatively little mass. This may explain the odd properties of certain X-ray binary systems that are suspected of harboring a black hole or neutron star.

$$\tau_{\text{accretion}} = (\ell n\, 2)\, \eta c\, \varkappa/8\pi\, G = 2 \times 10^8\ \eta\ \text{yr}. \tag{3}$$

A neutron star has $R_c \approx 10$ km, very nearly independently of the mass, and therefore we find

$$\tau_{\text{accretion}} = M_c\, \varkappa/4\pi c\, R_c = 7 \times 10^7\ (M_c/M_\odot)\ \text{yr}. \tag{4}$$

In both cases, the doubling time is amply long so as not, in itself, to contradict the continued existence of the composite star.

The actual lifetime of the diffuse component depends on the magnitude of L_c compared with L_d, the nuclear luminosity generated inside the diffuse component. If L_c is very small, the central collapsed object has little influence on the overlying star, even gravitationally, and the lifetime of the star is given by the usual expression[1], modified slightly here,

$$\tau_{\text{nuclear}} \approx 10^{10}\ (M/M_\odot)^{-2.5}\ (L/L_d)\ \text{yr}. \tag{5}$$

If L_c contributes significantly to the power radiated by the surface, L, the diffuse component will adjust its internal structure to accommodate the non-nuclear source of energy -- specifically, by lowering its core temperature until $L_d = L - L_c$. Since L_d is now smaller than L, the nuclear lifetime of the star will be longer. The large central input of energy will also lift the overlying layers, thereby expanding and cooling the gas and thus leading to a larger equilibrium radius than the normal one for a main-sequence star of mass M.

These arguments concerning the structure have been verified by calculations of relevant models for composite stars of 5–60 $M_\odot$ with $M_c/M \leq 10^{-3}$, assumed to be in complete hydrostatic and thermal equilibrium. As expected, the radius expansion is not very large because $R \propto L_d^{-1/18}$ due to the steep temperature dependence of the CN cycle. The surface luminosity L is scarcely affected.

If L_c exceeds L, no thermal adjustment of the structure is possible, and, even though L_c is less than the Eddington luminosity for the total M, secular instability will nevertheless ensue, leading to surface expansion either on a Helmholtz-Kelvin time scale,

$$\tau_{HK} = GM^2/RL_c \approx 10^8 \,(M/M_\odot)^{-2.5}\,(L/L_c)\ \text{yr}\ , \tag{6}$$

or, if the envelope becomes turbulent, on a hydrodynamical time scale,

$$\tau_{\text{dynamical}} = (R^3/GM)^{1/2} \approx (M/M_\odot)^{1/2}\ \text{hr}\ . \tag{7}$$

Most of the diffuse matter will be quickly lost to space, except for the matter gravitationally bound very close to the collapsed object, which will continue to accrete the remnant cloud surrounding it.

A rough criterion for stability against mass loss is therefore

$$L_c < L\ . \tag{8}$$

The precise value of L is not easy to guess. The surface luminosity is not solely determined by the mass and mean molecular weight of the star, especially under such strange circumstances. It will be affected somewhat by the gravitational and thermal presence of the collapsed object and by rotational angular momentum of the whole star. Further, if the collapsed object is a neutron star, gravitational (compressional) energy will be released from the body of the object as its mass grows. Nevertheless, a roughly correct picture will emerge if we adopt for L the normal equilibrium luminosity for a star of mass M.

In table 1, the maximum mass of a collapsed object consistent with inequality (8), with $L_c = L_{Edd}(M_c)$, is listed for several values of total mass M. The large change of M_c with M leaves little doubt that the results must be correct in order of magnitude. The ratio M_c/M is in most cases small enough that the direct gravitational influence of the central object will be negligible, as we had hoped.

A second possibility to consider is that the central collapsed object does not accrete matter at the Eddington rate. This possibility is realistic only in the case of a central neutron star, which we now consider. Let the neutron star form a dark degenerate core inside the diffuse star. As the core mass slowly grows as a result of hydrogen depletion in a burning shell around the core, the total configuration will approach that of a red giant. Unlike an ordinary red giant, however, there is no central helium or carbon flash to arrest the upward climb in luminosity (all of which is generated in the nuclear-burning shell). As a consequence, the star eventually attains the Eddington luminosity for its total mass M, whereupon secular instability ensues, as in the case just considered. Therefore, the criterion for stability is here

$$L_d < L_{Edd}(M) \ . \tag{9}$$

We have computed envelope models for composite stars of 10, 15, and 30 $M_\odot$ with luminosities ranging up to the Eddington limit, and have determined the maximum possible mass of the core that has a radius consistent with that of a stable neutron star. For 10 and 15 $M_\odot$, the maximum (and minimum) core masses were found to be about 0.1 $M_\odot$, which happens to be the lower limit for the mass of a stable neutron star. For 30 $M_\odot$, no core of small mass appears to exist at all. In all three cases, the permissible core masses are less than those shown in Table 1, which may therefore be taken as giving upper limits to the allowable mass of any collapsed object inside a static diffuse star.

From the numbers in Table 1, we find that, if the typical mass of a neutron star is ~1 $M_\odot$, stars of total mass less than about 20 $M_\odot$ (and perhaps higher) cannot accommodate quietly such an interloper at their centers. Since mass exchange in a close binary system is the most likely way to envelop a collapsed object by a diffuse star (see below), the maximum mass of a composite object in a binary system containing a neutron star is easily shown to be ~15 $M_\odot$, if we assume that the masses of the main-sequence progenitors of neutron stars are always less than 10 $M_\odot$. Hence all such composite objects will be secularly unstable. The masses of black holes produced by stellar implosions may range from ~1 $M_\odot$ on up, and their accommodation inside a diffuse star would be even more difficult, if not impossible.

Origin of the Composite Stars

A variety of circumstances might allow a compact object to reside (at least temporarily) at the center of an ostensibly normal star. If space is populated with particle-like black holes, then the gradual accretion of them by a massive gravitating object like the sun could build up a central black hole of $\sim 10^{-16}$ $M_\odot$ over the sun's lifetime.[2] Or, if isolated black holes of up to 10^{-6} $M_\odot$ exist and form the accretion centers for star formation, the sun could accommodate such a black hole with little visible effect, even if it were radiating accretion energy at its Eddington luminosity.[3] Alternatively, any collapsed object moving through a dense region of the interstellar medium at a slow enough velocity might eventually accrete a massive envelope, although this is more doubtful. It is well known that a red giant of low mass is already an incipient white dwarf embedded in a diffuse envelope; and, if the formation of a neutron star or black hole out of a red giant of higher mass is not attended by either complete expulsion of the envelope or immediate collapse of the whole star, a composite structure containing a central collapsed object and a diffuse envelope would be the result.

Close binary systems, however, provide the likeliest site for a complex remnant of this type. Normally, in a close binary system, the originally more massive star, evolving first, will fill its Roche lobe, transfer its envelope to its companion, and soon thereafter become a collapsed object, before the companion has evolved away from the main-sequence state.[4] If the formation of the collapsed object were to involve a sudden and large amount of mass loss from the system as a whole, the orbit of the remnant could be highly eccentric,[5,6] possibly penetrating the envelope of the companion. This diffuse envelope would suffer the effects of a changing tidal force, conversion of orbital into rotational angular momentum, loss of mass to the collapsed object, as well as frictional and accretional heating (possibly generating nuclear energy release), and would be at least partly dissipated into space. However, its radius would not be reduced very much simply as a result of the mass loss (since $R \propto M^{0.5}$ for main-sequence stars), but, on the contrary, would probably be distended considerably by the energy and angular-momentum input from the passages of the collapsed object. As the orbit of the object circularized and decayed as a result of tidal and atmospheric drag, the object would tend to settle toward the center of the main-sequence star. An alternative picture might be that the main-sequence star, as it evolved into a giant configuration, would "swallow up" the collapsed object if the mass of the latter star relative to the big star were so small that its Roche lobe could not accommodate rapid mass transfer from the big star.

The likeliest event of all, however, is that the mass of the collapsed object is not small in the above sense, with the consequence that this object succeeds in drawing off the envelope of the evolving big star. We thus note that massive accretion onto the collapsed object will occur only during the second phase of mass transfer in the system.[7] Since the secondary's surface area is so small, the transferred matter, which can possess considerable angular momentum, will form a rotating ring or disk around the tiny secondary before being accreted. In systems with ordinary main-sequence stars as secondaries, accretion of mass and of rotational angular momentum from the disk is known to be fairly swift, being completed by the end of the "rapid" phase of mass transfer from the primary.[8] During this phase, the primary loses mass at a rate that becomes as high as[4]

$$dM/dt \approx M/\tau_{HK} \approx 10^{-8}\ (M/M_\odot)^4 \qquad M_\odot\ yr^{-1} \quad . \tag{10}$$

At such a rate, mass will pile up on the collapsed object until the disk becomes almost spherical.[9,10,11] It may be that the build-up of a massive star around the collapsed object is faster than the dissipation of matter by the Eddington luminosity generated by the infall. However, we have just shown that, even if a massive diffuse star is accumulated in this way, it will very soon become secularly unstable (under most circumstances) and be blown away.

Therefore, we expect that an observed binary system containing a (perhaps disguised) black hole or neutron star as one component and a giant filling its Roche lobe as the other component should show a small ratio of the masses of the two components ($M_2/M_1 \leq 1$). In contrast, a large mass ratio ($M_2/M_1 \geq 1$) is already known to exist for ordinary binary systems near the end of the first phase of mass transfer, in which relatively little mass is lost from the system.[8] We have, thus, a test for the presence of a collapsed object, because it is very unlikely, on a time scale argument,[4,8] that mass transfer from the primary in either case has just begun, rather than almost ended. One cautionary reminder in interpreting such systems is that the primary is overluminous with respect to its mass, which should be taken as that of the dehydrogenized core of the star before mass loss.[12] However, the mass of the secondary will be essentially that of the collapsed object itself and not of the disk or cloud around it. The orbit is expected to remain circular because the (post-supernova) mass loss from the system, although fairly rapid and heavy, probably occurs on the Helmholtz-Kelvin time scale. Since much of the orbital angular momentum has gone into rotational angular momentum of the disk and has then been expelled along with the disk matter, the orbital period should be short.

These criteria for the presence of a collapsed object are notably satisfied in the case of the semi-detached binary systems Cyg X-1,[13,14,15] Her X-1,[16,17] Vel X-1,[18] and 2U 1700-37.[19] Probably Cen X-3[20] and SMC X-1[21,22,23] also satisfy the necessary conditions. Of course, the fact that the secondaries in these systems are compact but powerful X-ray emitters with a rapidly fluctuating intensity has already made them prime suspects as black holes or neutron stars.

In conclusion, we have found that secular instability is expected to quickly limit the amount of diffuse gas that can exist around a collapsed object whether it is radiating accretion energy or not. In a close binary system the time scale of the forced mass dispersal would be expected to be at most of the same order of magnitude as the time scale of mass transfer from the other component; the whole phase must therefore be very brief and hence rarely detected. Most observed semidetached X-ray binary systems with collapsed components are thus expected to be in the later phase in which the diffuse cloud around the compact object has relatively little mass.

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TABLE 1. Maximum mass M_c of a central collapsed object that is consistent with secular stability of the whole star of mass M

$M/M_\odot$	$M_c/M_\odot$	M_c/M	$M/M_\odot$	$M_c/M_\odot$	M_c/M
1	2×10^{-5}	2×10^{-5}	15	0.5	0.03
2	4×10^{-4}	2×10^{-4}	20	1.0	0.05
5	1×10^{-2}	3×10^{-3}	30	2.9	0.10
10	0.1	0.01	60	12.8	0.21